National Academies of Science

Committee on the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles – Phase 3

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July 16, 2018

Outline

- Introduction to OTAQ and NVFEL
- The Committee's Charge is Vitally Important
- NAS Recommendations Inform EPA's Work
- EPA's recent work
- Recommendations
- Conclusions
- Appendix: EPA publications and reports citations

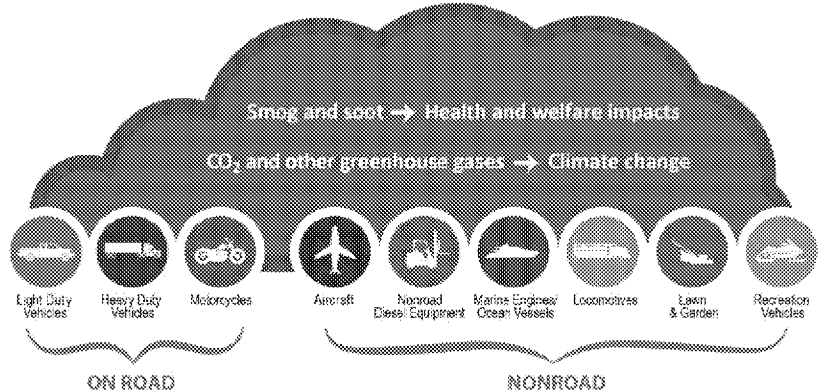
EPA's Mission

To protect human health and the environment.

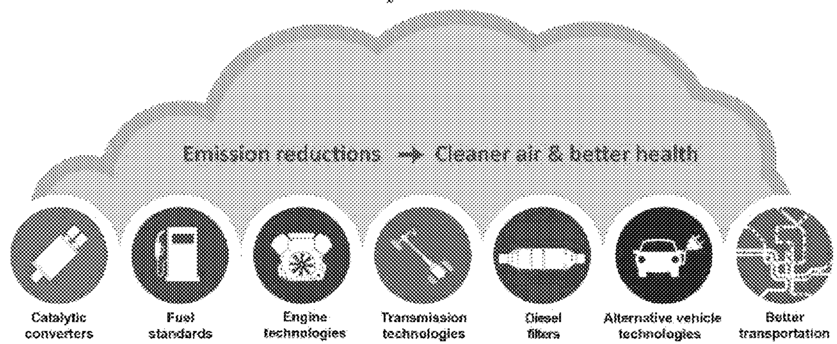
Office of Transportation and Air Quality

To protect human health and the environment by reducing air pollution and greenhouse gas emissions from mobile sources and the fuels that power them, advancing clean fuels and technology, and encouraging business practices and travel choices that minimize emissions.

Sources of Transportation Air Pollution



Solutions for Transportation Air Pollution



EPA's National Vehicle and Fuel Emissions Laboratory

- State of the art, ISO 14001 certified, national laboratory responsible for testing, certification, and research on air emissions from a wide range of transportation sources
- Tests cars, trucks and engines to ensure they meet emissions standards throughout their useful lifetime
- Researches and performs testing to inform new and updated emissions standards for air pollutants
- Develops and implements test methods for measuring emissions from vehicles and engines
- Assesses promising emissions reduction technologies
- Benchmark for all other automotive emissions labs world-wide: ISO/IEC 17025 accredited – the gold standard for data quality

Ann Arbor, MI

- ✓ Light-duty chassis testing
- ✓ Heavy-duty chassis testing
- ✓ Engine emissions testing
- ✓ Portable emission measurement systems
- ✓ Fuels and chemistry analysis

This NAS Committee's Charge is Vitally Important

- 2025-2035 is a critical time frame for the transportation sector, especially the light-duty sector
- The industry, marketplace, and consumers will be changing rapidly – how will this impact Federal and state policies?
- For EPA, what will this mean for emissions, air quality, the climate, the environment, and public health?
- OTAQ is a resource for this Committee
  - For the 2010 and 2015 report committees, OTAQ provided ~20 technical presentations as well as data, reports, and assessments

NAS Recommendations Inform EPA's Work

EPA followed through on many recommendations from the 2015 NAS Report. Examples:

- **Full vehicle simulations and teardown cost analysis** (Recommendation 8.3): *"The committee notes that the use of full vehicle simulation modeling in combination with lumped parameter modeling and teardown studies contributed substantially to the value of the Agencies' estimates of fuel consumption and costs, and it therefore recommends they continue to increase the use of these methods to improve their analysis."*
  - EPA has continued cost teardown studies of fuel efficient technologies, including diesel engines, updated turbo-downsized engine, 8-speed transmissions, CVTs, high-efficiency gearbox, mild hybrids, cost updates to past teardowns
  - EPA has continued to enhance the ALPHA full-vehicle simulation model
- **Engine maps** (Recommendation 2.1): *"For spark ignition engines these [full vehicle] simulations should be directed toward the most effective technologies that could be applied by the 2025 MY to support the midterm review of the CAFE standards. The simulations should use either engine maps based on measured test data or an engine-model-generated map derived from a validated baseline map in which all parameters except the new technology of interest are held constant."*
  - EPA/NVFEL has performed benchmarking testing on more than 30 vehicles and all completed test results are publicly available
  - See next slides for vehicle listings, and Appendix for publication citations; benchmarking data packets available at:

    https://www.epa.gov/vehicle-and-fuel-emissions-testing/benchmarking-advanced-low-emission-light-duty-vehicle-technology#test-data
- **Manufacturer Learning-by-doing Cost Reductions** (Recommendation 7.2): *"The Agencies should also continue to conduct and review empirical evidence for the cost reductions that occur in the automobile industry with volume, especially for large-volume technologies that will be relied on to meet the CAFE/GHG standards."*
  - *EPA commissioned a Learning literature review and assessment. Peer-reviewed report:* https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100PUSX.PDF

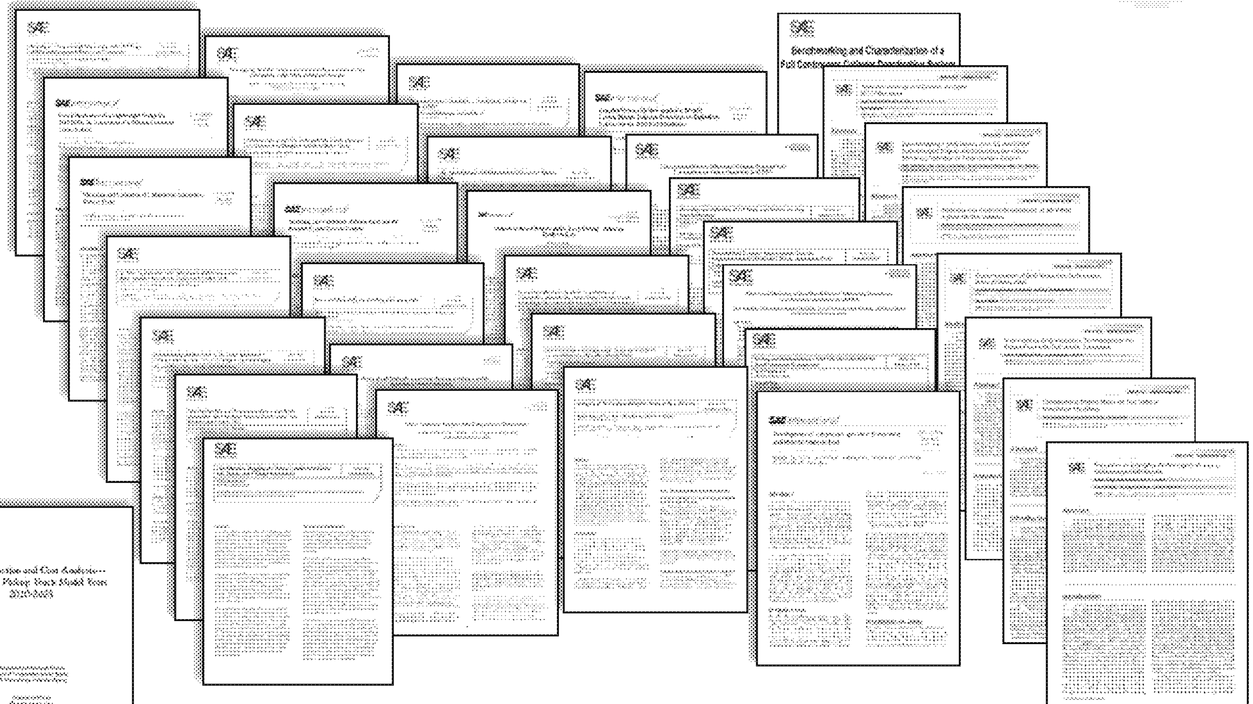
EPA's Recent Work

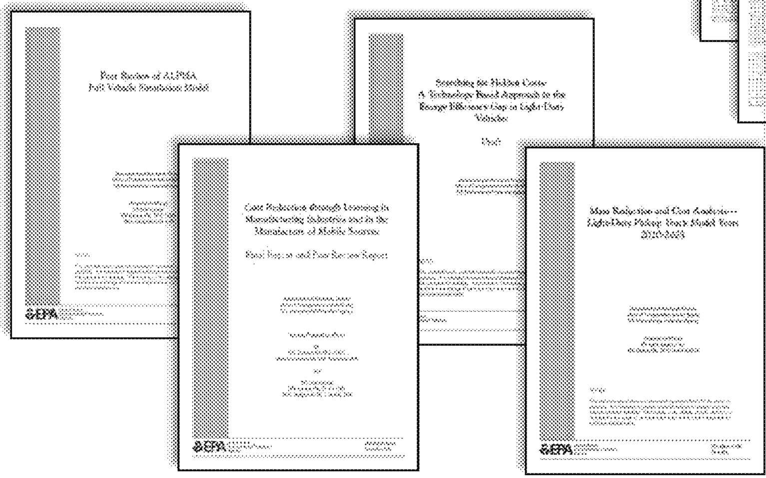
- NVFEL **benchmarking testing of 30 vehicles** across wide range of powertrains & segments
  - Provides critical up-to-date engine and transmissions inputs for vehicle simulation modeling; all data are publicly available
- In-house **full-vehicle simulation modeling** (ALPHA)
- In-house **technology/cost optimization modeling** (OMEGA)
- **Cost teardown studies** of key technologies
- Updated **baseline vehicle fleet** to MY2016 (MY2017 update ongoing)
- Continued studies of **VMT rebound** effect
- **Consumer issues**:
  - Role of fuel economy in purchase decisions
  - Consumer satisfaction with fuel efficient technologies
    (research through professional auto reviews and Strategic Vision data of new car owner surveys)
  - Consumer willingness to pay (WTP) for vehicle attributes
    (commissioned study through RTI, with subject matter expert Dr. David Greene)
  - Potential tradeoffs
  - Affordability
  - Energy paradox (or "energy efficiency gap")

EPA Technical Information Available to the Public

Wide range of peer-reviewed publications and presentations:

- Technical reports
- Publications, including more than 30 SAE papers since 2013
- Technical conference presentations





EPA continually assesses latest developments

In addition to our own research, EPA keeps abreast of latest developments through review of hundreds of papers/reports in the literature, attending technical conferences, and stakeholder dialog. Example conferences attended by EPA staff in recent years:

- **Aachen Colloquium, 2015 & 2016**
- **Advanced Automotive Battery Conference, 2014-2017**
- **Allied Social Sciences Association Annual Conference, 2014-2018**
- **Asilomar Transportation and Energy Conference, 2015 & 2017**
- **ASME ICE Fall Technical Conference, 2014-2017**
- **Association of Environmental & Resource Economists Conference, 2015-2017**
- **Automotive World Megatrends Fuel Economy Detroit, 2014, 2016 & 2017**
- **Autonomous and Connected Detroit, 2017**
- **Clemson University Global Tire Conference, 2017**
- **CTI Symposium USA: Automotive Transmissions, HEV and EV Drives, 2014-2018**
- **DOE Annual Merit Review , 2014-2018**
- **DOE Cross Cut Lean Exhaust Emissions Reduction Simulation, 2014-2017**
- **Electric Vehicle Symposium (EVS29 & 30), 2016 & 2017**
- ETH Conference on Combustion Generated Nanoparticles, 2017 & 2018
- FKFS Progress in Vehicle Aerodynamics , 2017
- Global Automotive Lightweight Materials - Detroit Conference, 2014, 2015 & 2017
- Great Designs in Steel, 2014-2018
- International Energy Economics Association meeting, 2014
- ITB Advanced Thermal Management, 2017-2018
- Mathworks Automotive Conference, 2014-2018
- North American Automotive Metals Conference, 2015
- SAE Government-Industry Meeting, 2014 - 2018
- SAE High-Efficiency IC Engine Symposium, 2016-2018
- SAE Hybrid & Electric Vehicle Technologies Symposium, 2015-2018
- SAE Light-duty Emissions Control Symposium, 2014 & 2017
- SAE North American International Powertrain Conference, 2015-2017
- SAE Thermal Management Systems Symposium , 2015 & 2016
- SAE World Congress, 2014-2018
- Society for Benefit-Cost Analysis Annual Conference, 2015-2018
- Society of Plastics Engineers AutoEPCON, 2017
- The Battery Show Europe, 2018
- The Battery Show, North America Conference, 2014-2018
- Transport Canada eTV Forum, 2016
- Transportation Research Board Annual Meeting, 2014-2018
- TU Automotive Detroit 2018, 2018
- U. Michigan Transportation Economics, Energy, & Environment, 2014-2017
- U. Michigan Transportation Research Institute Powertrain Conference, 2017 & 2018
- U. of Michigan/MSU/W. Michigan University Environmental and Energy Economics Day, 2014-2017
- Vienna Motor Symposium, 2015-2018
- Wards Auto Outlook Conference, 2017

EPA In-depth Evaluation of Advanced Powertrains

Technology Effectiveness: Gasoline Engine Benchmarking

Turbocharged engines
- 1.6L Ford EcoBoost –2013 Ford Focus (Euro)
- 1.6L Ford EcoBoost – 2013 Ford Escape
- 1.6L PSA Valvetronic turbo – 2012 Peugeot
- 2.7L V6 EcoBoost (2015 Ford F150)
- 1.5L I4 (2016 Honda Civic)
- 2.5L I4 Skyactiv-G (Mazda CX-9)
- Applied publicly available engine maps:
  - 1.0L I3 EcoBoost (2014 Ford Fiesta) (more efficient than the 2013 Ford 1.6L EcoBoost)
  - 2.0L I4 (VW) with and without Miller cycle operation
  - 1.4L I4 (VW) – from a copyrighted 2016 Ricardo Report

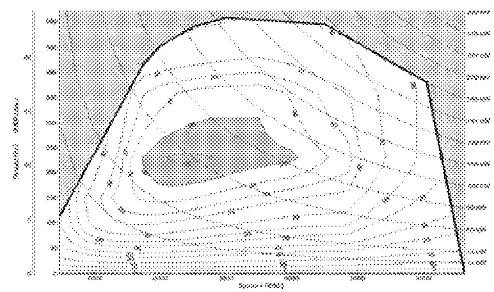
Naturally aspirated engines
- 2.5L I4 Ecotec engine - 2013 GM Malibu
- 2.5L I4 Skyactiv – 2014 Mazda 6
- 2.0L I4 Skyactiv – 2014 Mazda 3 (13:1 CR)
- 2.0L I4 Skyactiv – 2014 Mazda 3 (14:1 CR – Euro)
- 4.3L V6 Ecotec3 with cylinder deac - 2014 GM Silverado 1500 2WD
- 2.5L I4 Toyota TNGA – 2018 Toyota Camry (in-process)
- Applied publicly available maps:
  - 2.5L I4 TNGA prototype engine (from Toyota Aachen paper)

Cylinder deactivation
- 4.3L V6 Ecotec3 with cylinder deac - 2014 GM Silverado 1500 2WD
- 6.2L V8 GM – 2011 Tula demonstration of 'dynamic skip fire' in GMC Denali
- 1.8L I4 VW – 2015 Tula demonstration of 'dynamic skip fire' in VW Jetta (in-process)
- Applied publicly available data:
  - Tula 'Dynamic Skip Fire' I4 turbocharged and V8 naturally aspirated engines

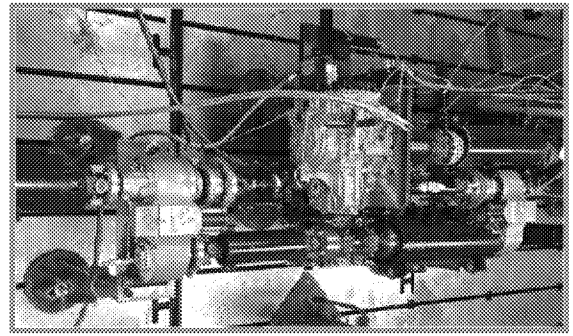
Other EPA testing & modeling
- Prototype Mazda SkyActiv with 14:1 CR + Cooled EGR and high energy ignition
- GT-Power modeling of cooled-EGR and Variable Nozzle Turbocharger/Variable Geometry Turbocharger (VNT/VGT)

2015 Ford F150 2.7L EcoBoost Engine

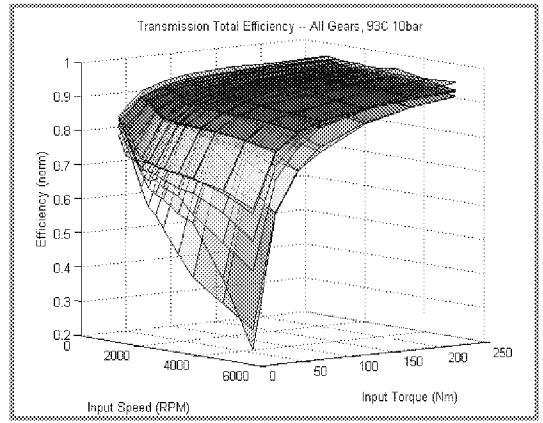
Current Production Engine, 24-bar BMEP, Turbocharged GDI with DCP



Technology Effectiveness: Transmission Benchmarking



Transmission Benchmarking and Resultant Torque/Speed/Efficiency Curve



<u>Benchmarked key transmissions to obtain efficiency and operational maps</u>

- GM 6T40 6-speed automatic transmission (AT) from 2013 MY Malibu
- 2014 GM Silverado 6-speed
- FCA 845RE 8-speed AT from 2014 Ram 1500 Pickup Truck
- Jatco CVT8 transmission
- 2016 Honda CVT

<u>Applied transmission maps provided by industry</u>

- DCT 6-speed
- DCT 7-speed
- CVT
- Jatco CVT7
- Jatco CVT8
- Toyota CVT

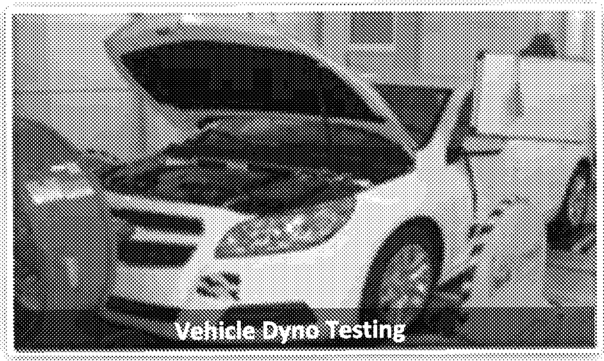
<u>Benchmarked several vehicles to characterize transmission shift schedules, torque convertor lock-up, and vehicle controls</u>

- 2013 GM Malibu – 6-speed AT
- 2014 Dodge Chargers – 5-speed AT & 8-speed AT
- 2015 Volvo S60 – 8 speed AT
- Ford F150 and GM Silverado – 6-speed
- Ram 1500 HFE – 8 speed AT
- 2016 Honda CVT
- More than a dozen other late model vehicles (next slide)

Technology Effectiveness: Gasoline and Diesel Vehicle Benchmarking

<u>Benchmarked Vehicles With Naturally Aspirated Engines</u>

2013 Chevrolet Malibu (base)
2013 Chevrolet Malibu Eco
2013 Chevrolet Volt
2013 Mercedes E350
2013 Altima SV
2014 US Mazda 6
2014 US Mazda 3
2014 Dodge Charger 5-spd
2014 Dodge Charger 8-spd
2014 RAM 1500 HFE
2014 Chevy Silverado 1500 2WD
2016 Chevrolet Malibu
2018 Toyota Camry TNGA
2011 GMC Denali (GM 6.2L V8 with Tula 'Dynamic Skip Fire')


Vehicle Dyno Testing

Applied publicly available data:
Tula 'Dynamic Skip Fire' on V8 naturally aspirated

Planned Future Vehicles
2019 Chevrolet Silverado (5.3L with DFM cylinder deac)
2018 Mazda 6 (2.5L I4 with cylinder deac)

<u>Benchmarked Vehicles With Turbo Engines</u>

2013 Escape
2013 Focus (Euro)
2014 RAM 1500 EcoDiesel
2015 Ford F-150 (6-speed)
2017 Ford F-150 (10-speed)
2015 Volvo S60 T5
2016 Acura ILX
2016 Malibu 1.5L turbo
2016 Honda Civic 1.5L turbo
2016 Mazda CX-9 2.5L turbo
2015 VW Jetta (VW 1.8L I4 with Tula 'Dynamic Skip Fire' in-process)

Applied publicly available data:
Tula 'Dynamic Skip Fire' on I4 Turbocharged

Planned Future Vehicles
2018 Jeep Wrangler (2.0L I4 with eTorque)
2019 Infiniti QX50 (2.0L I4 with variable CR)
2019 Mazda 3 (2.0L SkyActiv X SPCCI)

EPA Investigation on Power/Fuel Economy Tradeoffs

ALPHA full vehicle simulation was used to determine 0-60 acceleration performance and CO_2 emissions for a generic vehicle with five different powertrains:

- 1980 carbureted engine + 3AT
- 2007 PFI engine + 5AT
- 2013 GDI engine + 6AT
- 2017 TC engine + 8AT
- Future (2025) TC engine + adv 8AT

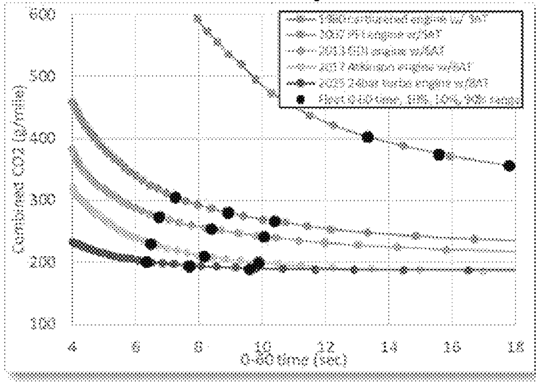
Engine power was swept, keeping other parameters constant.

The tradeoff (<u>percent change in CO_2 per percent change in acceleration time</u>) was examined, over 0-60 times of fleet in the year indicated.

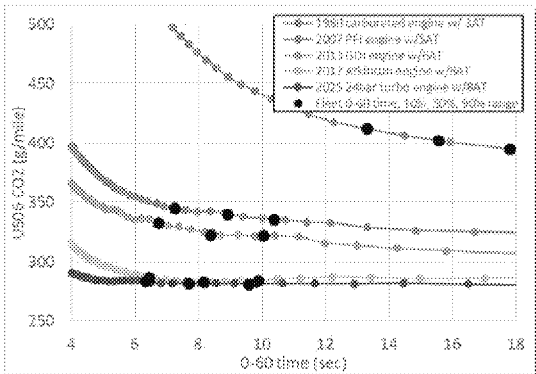
Caveat: This simplified analysis assumes only changes to engine power, and not other vehicle parameters.

Published in part in: Moskalik, A., Bolon, K., Newman, K., and Cherry, J. (2018) "Representing GHG Reduction Technologies in the Future Fleet with Full Vehicle Simulation," SAE Technical Paper 2018-01-1273, doi:10.4271/2018-01-1273.
Publication of further results in process.

Combined FTP-HW Cycle



US06 (more aggressive cycle)



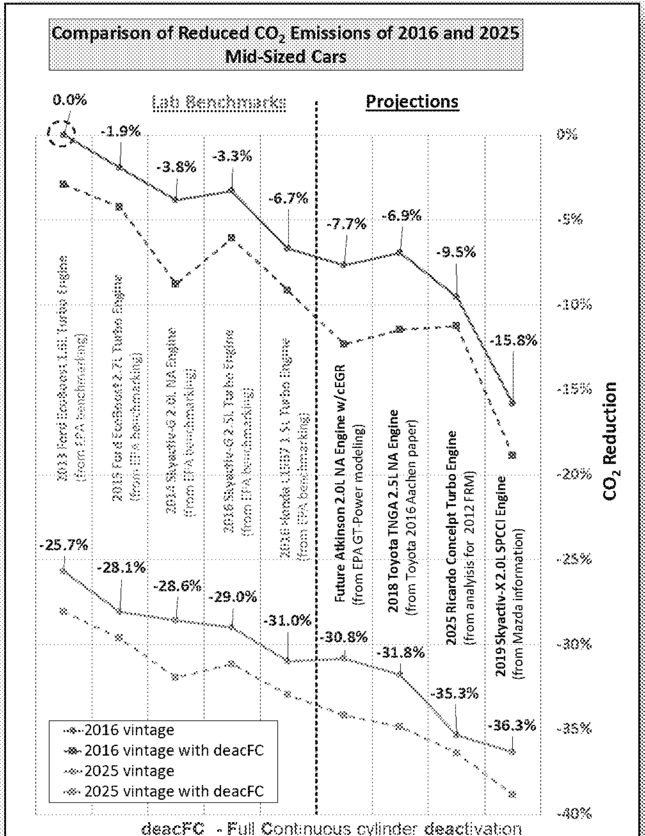
Comb. Cycle Data: Powertrain	0-60 average	CO_2 @ 0-60 av.	Slope, 10th-90th %	(%Δ CO_2)/ (%Δ 0-60)
1980 carbureted	15.57	375	-10.5	-0.43
2007 PFI	8.91	281	-12.1	-0.37
2013 GDI	8.39	254	-9.3	-0.30
2017 Atkinson	8.16	210	-9.1	-0.35
2025 24bar turbo	7.69	195	-3.4	-0.14

Combined cycle tradeoffs change only slightly over 1980-2017, but may be much "flatter" in the future, indicating that increasing performance has less effect on CO_2.

US 06 Data: Powertrain	0-60 average	CO_2 @ 0-60 av.	Slope, 10th-90th %	(%Δ CO_2)/ (%Δ 0-60)
1980 carbureted	15.57	402	-3.8	-0.15
2007 PFI	8.91	340	-2.9	-0.07
2013 GDI	8.39	323	-3.3	-0.08
2017 Atkinson	8.16	283	-0.7	-0.021
2025 24bar turbo	7.69	282	-0.6	-0.017

US06 tradeoffs are generally much flatter, and tradeoffs may be approaching zero for more the aggressive US06 cycle.

EPA Uses Detailed Benchmark Data and Models to Project Longer-term (2025+) Potential for Next-Generation Internal Combustion Engines and Vehicles

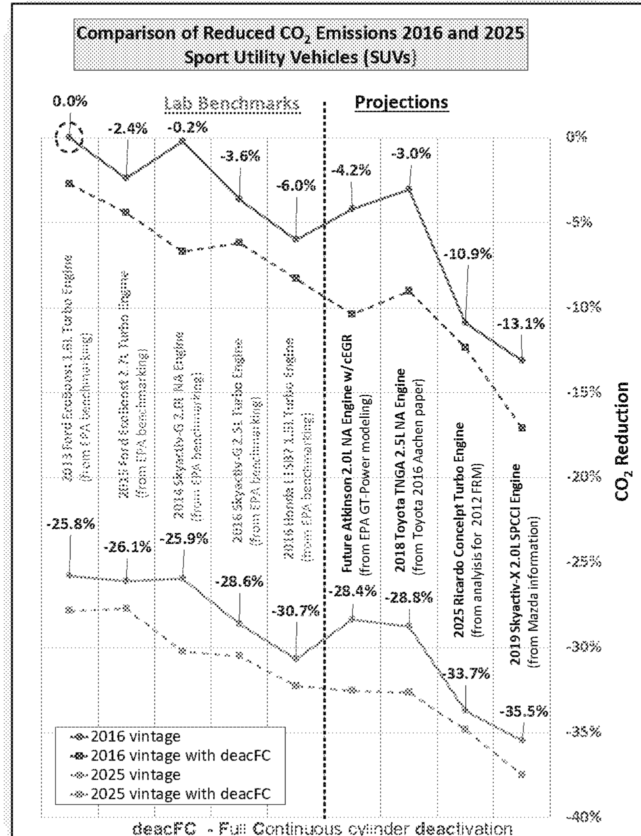


Engine
2013 Ford EcoBoost 1.6L Turbo Engine[1]
2015 Ford EcoBoost 2.7L Turbo Engine
2014 Mazda Skyactiv-G 2.0L NA Engine
2016 Skyactiv-G 2.5L Turbo Engine
2016 Honda L15B7 1.5L Turbo Engine
Future Atkinson Engine w/cEGR[2]
2018 Toyota TNGA 2.5L N/A Engine[3]
2025 Ricardo Concept Turbo Engine[4]
2019 Skyactiv-X 2.0L SPCCI Engine[5]

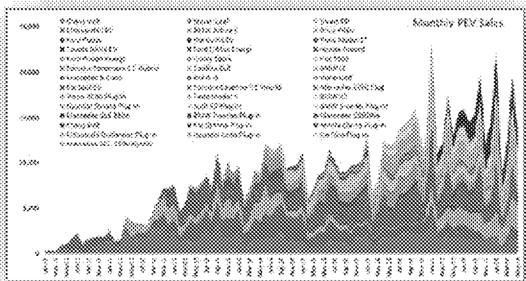
Effect on CO_2 Depends on Factors

- Engine size v. vehicle loading
- Implementation & architecture (e.g., I4, V6 etc.)
- Implementation of strategies (e.g., cylinder deacFC fly zone)
- Other elements in powertrain (e.g., where transmission allows engine to operate)

Reference: EPA Presentation at SAE 2018 High Efficiency IC Engine Symposium, D. Barba, April 2018

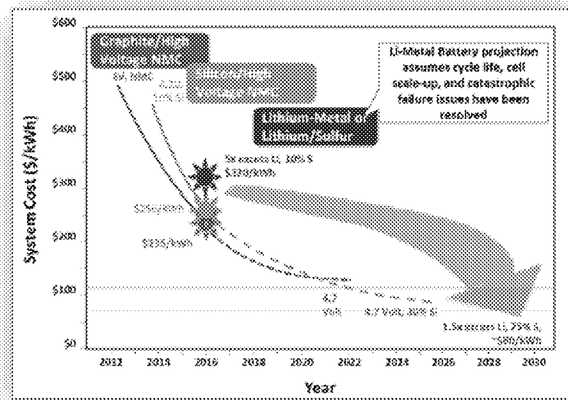


Emerging Trends in . . .



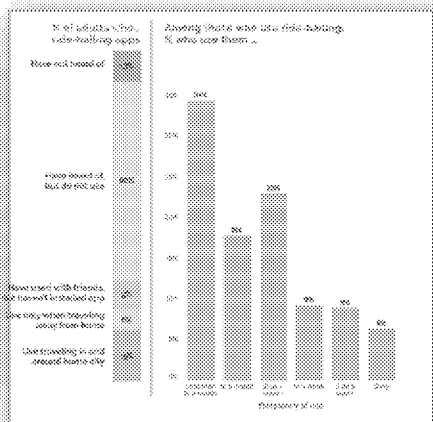
PEVs

Argonne National Laboratory



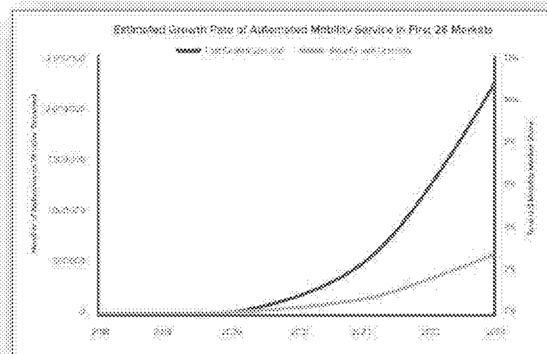
Energy Storage

Batteries and Electrification R&D Overview, US DOE Office of Energy Efficiency and Renewable Energy, Steven Boyd, June 18, 2018



Shared Mobility

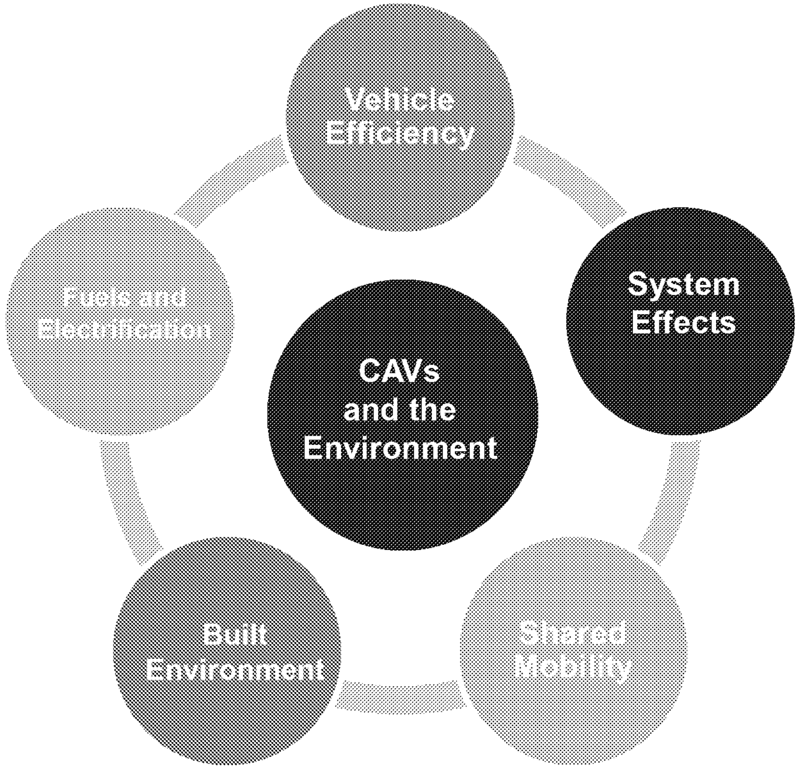
Clewlow, Regina R. and Gouri S. Mishra (2017) *Disruptive Transportation: The Adoption, Utilization, and Impacts of Ride-Hailing in the United States.* Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-17-07



Automation

Walker, Jonathan and Charlie Johnson. *Peak Car Ownership: The Market Opportunity of Electric Automated Mobility Services.* Rocky Mountain Institute, 2016. http://www.rmi.org/peak_car_ownership

Emerging Trends Will Impact Energy Use and the Environment



- Vehicle optimization, drive smoothing, and decision-making protocols
- System-wide factors such as connectivity, routing, and travel demand
- Shared mobility's influence on right-sizing, mode-shifting, peak travel
- The built environment's influence on a transforming transportation system
- Fuel choices and refueling infrastructure

Analytical work to date shows a wide range of estimates of potential environmental impacts from new mobility

Source: Simon K.; Alson, J; Snapp, L; Hula, A. "Can Transportation Emission Reductions be Achieved Autonomously?" *Environ. Sci. Technol.*, 2015, 49 (24), pp 13910–13911.

Recommendations from EPA/OTAQ

What areas of technical and policy matters does EPA suggest the Committee focus on for the 2025-2035 time frame?

- **How and when will the transportation paradigm shift?**
  - When will EVs reach a tipping point in market acceptance for consumer market?
  - Will shared mobility enhance or replace transit? Under what conditions?
  - When will automated mobility services capture the US mobility market?
- **What are the energy and environmental impacts of such a shift?**
  - With the emergence of autonomous vehicles, what factors will be important to address to have a positive environmental result?
  - What does the fleet makeup in 2030-2035 mean for criteria pollutants?
- **How can we best assess this future?**
  - How can we use data to more quickly model the rapidly emerging changes in transportation?
- **What is the most effective framework for future GHG standards?**
  - Test procedures and fuels established in 1975 do not capture real world driving and/or changes to low carbon fuels -- future vehicle ownership and/or mobility scenarios will most likely not be represented by the FTP and Highway test cycles
    - In its 2015 report the NAS recommended the application of 5-cycle testing to better represent real-world driving
  - Are there aspects of the current GHG regulations and test procedures that could better incentivize reducing “real-world” emissions over reducing emissions on the test cycles?
  - What other regulatory frameworks might be available to reduce GHG emissions under changing ownership and mobility solutions?
- **NAS recommendations on strengths & weaknesses of EPA’s methodologies and approaches, areas where EPA should focus**

Conclusions

- EPA appreciates the Committee members' commitment to this effort, and stands ready to assist in any way that would be most valuable for the Committee.

- As we've done for past NAS Committees, EPA would be glad to assist the Committee in understanding any of our technical work in more detail, including an open invitation to visit NVFEL for further technical dialog.

- The Committee's report expected to be issued in 2020-2021 will be valuable in informing U.S. transportation environmental policies for the 2025-2035 timeframe.

Appendix:
EPA Publications and Reports

SAE Papers

2013 SAE Paper Citations

- Sciance, F., Nelson, B., Yassine, M., Patti, A. et al., "**Developing the AC17 Efficiency Test for Mobile Air Conditioners**," SAE Technical Paper 2013-01-0569, 2013, https://doi.org/10.4271/2013-01-0569.
- Dagci, O., Pereira, N., and Cherry, J., "**Maneuver-Based Battery-in-the-Loop Testing - Bringing Reality to Lab**," SAE Int. J. Alt. Power. 2(1):7-17, 2013, https://doi.org/10.4271/2013-01-0157.
- Lee, B., Lee, S., Cherry, J., Neam, A. et al., "**Development of Advanced Light-Duty Powertrain and Hybrid Analysis Tool**," SAE Technical Paper 2013-01-0808, 2013, https://doi.org/10.4271/2013-01-0808.
- Lee, S., Lee, B., McDonald, J., Sanchez, L. et al., "**Modeling and Validation of Power-Split and P2 Parallel Hybrid Electric Vehicles**," SAE Technical Paper 2013-01-1470, 2013, https://doi.org/10.4271/2013-01-1470.
- Lee, S., Lee, B., McDonald, J., and Nam, E., "**Modeling and Validation of Lithium-Ion Automotive Battery Packs**," SAE Technical Paper 2013-01-1539, 2013, https://doi.org/10.4271/2013-01-1539.
- Caffrey, C., Bolon, K., Harris, H., Kolwich, G. et al., "**Cost-Effectiveness of a Lightweight Design for 2017-2020: An Assessment of a Midsize Crossover Utility Vehicle**," SAE Technical Paper 2013-01-0656, 2013, https://doi.org/10.4271/2013-01-0656.

2014 SAE Paper Citations

- Hula, A., Alson, J., Bunker, A., and Bolon, K., "**Analysis of Technology Adoption Rates in New Vehicles**," SAE Technical Paper 2014-01-0781, 2014, doi:10.4271/2014-01-0781.
- Lee, S., Cherry, J., Lee, B., McDonald, J. et al., "**HIL Development and Validation of Lithium-Ion Battery Packs**," SAE Technical Paper 2014-01-1863, 2014, doi:10.4271/2014-01-1863.

2015 SAE Paper Citations

- Newman, K., Kargul, J., and Barba, D., "**Development and Testing of an Automatic Transmission Shift Schedule Algorithm for Vehicle Simulation**," SAE Int. J. Engines 8(3):2015, doi:10.4271/2015-01-1142.
- Newman, K., Kargul, J., and Barba, D., "**Benchmarking and Modeling of a Conventional Mid-Size Car Using ALPHA**," SAE Technical Paper 2015-01-1140, 2015, doi:10.4271/2015-01-1140.
- Stuhldreher, M., Schenk, C., Brakora, J., Hawkins, D. et al., "**Downsized Boosted Engine Benchmarking and Results**," SAE Technical Paper 2015-01-1266, 2015, doi:10.4271/2015-01-1266.
- Moskalik, A., Dekraker, P., Kargul, J., and Barba, D., "**Vehicle Component Benchmarking Using a Chassis Dynamometer**," SAE Int. J. Mater. Manf. 8(3):2015, doi:10.4271/2015-01-0589.
- Safoutin, M., Cherry, J., McDonald, J., and Lee, S., "**Effect of Current and SOC on Round-Trip Energy Efficiency of a Lithium-Iron Phosphate (LiFePO4) Battery Pack**," SAE Technical Paper 2015-01-1186, 2015, doi:10.4271/2015-01-1186.
- Newman, K., Dekraker, P., Zhang, H., Sanchez, J. et al., "**Development of Greenhouse Gas Emissions Model (GEM) for Heavy- and Medium-Duty Vehicle Compliance**," SAE Int. J. Commer. Veh. 8(2):2015, doi:10.4271/2015-01-2771.

2016 SAE Paper Citations

- Kargul, J., Moskalik, A., Barba, D., Newman, K. et al., "**Estimating GHG Reduction from Combinations of Current Best-Available and Future Powertrain and Vehicle Technologies for a Midsized Car Using EPA's ALPHA Model**," SAE Technical Paper 2016-01-0910, 2016, doi:10.4271/2016-01-0910.
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